This power limit is determined by thermal and nonlinear limits that combine to prevent further power scaling, irrespective of increases in mode size. However, based on practical considerations for the fiber amplifiers bend diameter, we have also found that there is a practical limit to the achievable mode size; and that for this MFD there is an optimum fiber length that results in a laser whose maximum output power is 10-20 kW with good beam quality. This output power range, therefore, constitutes a practical physical limit to scaling the power of conventional fiber lasers.

Our models show that by moving from circularly-symmetric waveguides to ribbon-like rectangular-core fiber waveguides, the single-aperture power limit can be raised from 10-20 kW to >100 kW. The ribbon fiber waveguide has a rectangular cross sectional core with a high width-to-thickness aspect ratio. In such a structure the thin dimension (x) is single-moded and the wide dimension (y) is multi-moded. The fiber is coiled only in the x-direction. Since higher-order-modes (HOM) are less susceptible to bend loss and mode mixing, we choose to propagate a particular HOM (in the y-direction) in the ribbon fiber. The area of the waveguide and the mode's effective area can then be scaled by simply increasing the waveguide width. These ribbon fiber amplifiers can guide a higher-order mode, with a larger effective cross-sectional active area, and therefore, generate much higher output power than is possible in circular-core fibers.

In summary, we have discussed the design, simulation, and experimental results of mode converters with the capability to transform a fundamental (LP_{01}, TEM_{00}) output mode of a seed laser to a predetermined higher-order-mode of a rectangular-core ribbon fiber amplifier. The conversion is accomplished via two phase plates. The first phase plate is in the near field of the seed laser output beam waist and the second phase plate is in the near-field of the ribbon fiber facet. The required spatial profiles for the phase-shifting elements are derived via a Gerchberg-Saxton algorithm, for example. Phase retrieval and overlap efficiency calculations, based on experimental measurements of the intensities in the fiber-facers near and far-fields, show that the mode-conversion efficiency is ≈84%. Other phase reconstruction techniques, including genetic algorithms, have the potential to further improve the performance of the basic embodiments described herein. As discussed in "Mode-Converters for Rectangular-Core Fiber Amplifiers to Achieve Diffraction-Limited Power Scaling" 17 Dec. 2012/Vol. 20, No. 27 OPTICS EXPRESS 28800, incorporated herein by reference, we also demonstrate a mode-converter system that converts a single HOM of a ribbon fiber back to a diffraction-limited TEM_{00} mode. Conversion efficiency is a record 80.5%.

Those skilled in the art will appreciate that, instead of employing a mode converter that transforms a fiber LP_{01} into a single HOM (as described above), one can, alternately, design a mode converter capable of transforming an LP_{01} seed beam into a superposition of HOMs that launch into the ribbon fiber amplifier. This multi-mode approach may minimize the presence of "hot spots" in the ribbon, fiber (recall that a single HOM possesses multiple lobes), by homogenizing the intensity amongst the guided modes in the fiber, which may otherwise result in undesirable nonlinear optical effects, optical damage, color-center formation, etc. Adaptive optical compensation augmentations can be used to compensate for spatial modal dispersion, resulting in a high-power, diffraction-limited system output.

The skilled artesian will also appreciate that mode converters can be designed to provide coupling of a given mode in one structure into a given mode in another, differently configured, structure. As an example, the mode-conversion technique described herein can enable the transformation of high-power optical beams to classes of Bessel-mode beams, for enhanced focal properties. Related embodiments include Raman fiber amplifiers, such as gas-filled hollow-core photonic crystal fibers, in place of solid-core ribbon fibers.

Mode conversion modules can also be utilized to enhance the performance of a broad-class of optically pumped solid-state crystalline lasers as well as optically pumped atomic vapor lasers. In the former case, side-pumped rod-based and planar based (slab) solid-state lasers can possess a significant amount of pump absorption along the edges of the crystal, resulting in a non-uniform gain profile, with a low-gain central region. Resonator designs, as well as MOPA designs, that emphasize high-quality modal output, often result in wasted (i.e., unused) stored energy in the gain medium. This follows, since a TEM_{00} guided mode doesn't necessarily result in an optimal spatial overlap with an annular pump-beam absorption profile. By employing a mode converter to transform a fundamental resonator (or, amplifier) mode in a higher-order "doughnut" mode, one expects an improvement in the pump/signal spatial overlap and, therefore, the system extraction efficiency. A similar mode transformation methodology can be applied to the optical pumping of atomic vapor lasers, so that the pump absorption profiles and the laser's modal profiles can be optimally matched, resulting in enhanced laser efficiency. Finally, the use of mode converters can also, in some cases, increase the gain threshold for deleterious parasitic oscillation mechanisms.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the disclosure, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

FIG. **1** depicts a basic mode-conversion system capable of transforming a TEN_{00} mode to a high-order guided-wave mode, HOM (viz., a 7th order eigenmode), of a rectangular-core fiber.

FIG. **2** shows a cross-section of a ribbon fiber facet comprised of a rectangular core whose width is 5 μm and length is 50 μm.

FIG. **3** shows a functional flow chart depicting the operations typical of a Gerchberg-Saxton phase retrieval algorithm.

FIG. **4** shows a single-pass laser system using a mode converter to transform a fundamental mode of a fiber laser (LP_{01}) into a specific high-order mode of a ribbon fiber amplifier.

FIG. **5**A depicts the amplitude of a low-order mode, defining one of two constraints used in the simulation and design of a mode converter.

FIG. **5**B depicts the amplitude of a high-order mode, defining the second of two constraints used in the simulation and design of a mode converter.

FIG. **5**C shows simulation results, which yield a phase profile (associated with the field amplitude in FIG. **5**A), as determined via a phase retrieval algorithm, in the design of a mode converter.

FIG. **5**D shows simulation results, which yield a phase profile (associated with the field amplitude in FIG. **5**B), as determined via a phase retrieval algorithm, in the design of a mode converter.

FIG. **6** shows an experimental setup of a mode-converter system that uses two spatial light modulators, as programmable diffractive optic elements, to impose the required phase profiles onto a propagating mode at a pair of Fourier conjugate planes.